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Air Force Research Laboratory

Integrity ★ Service ★ Excellence

Health Management and Service Life for Air Force Missiles

Date: 26 09 2011

Major Andrew Sincock

Chief

Motor Branch

Air Force Research Laboratory

Agenda

- Introduction
- Motivation
- Background / Previous Successes
- Current Work
- Tech Needs
- Summary and Conclusions

Introduction

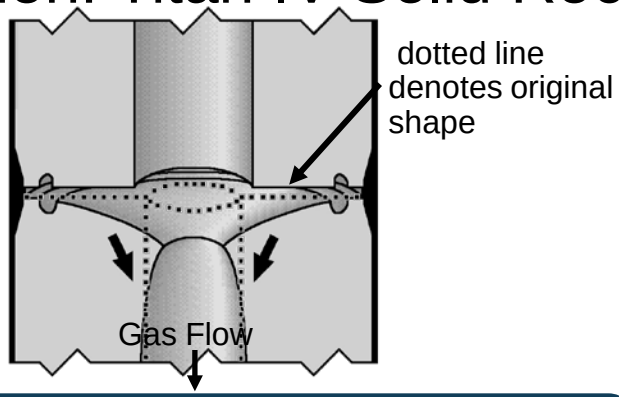
- **Solid motors are:**
  - **Simple: few moving parts, provide rapid response**
  - **Storable: no costly cryogenic or pressure systems required**
  - **Reliable: ready when needed, even after extended deployment**

- **However, solid rocket motors are:**
  - **Mechanically and chemically complex**
  - **Designed with small margins**
  - **Dynamic, changing with age and environmental exposure**
  - **Often required to function long beyond the design life**
  - **Often subjected to unexpected environments**
  - **Generally not capable of maintenance/repair**

Motivation

Structural-Ballistic Interaction: Titan IV Solid Rocket Motor failure

Soft propellant deflects into flow, causes unexpected overpressure



Cost: Test stand damaged, Titan SRM destroyed, ~14 month program delay

Aging Failure: AIM-7 Sparrow explodes on launch from F-15

Chemical reaction of insulation curative degrades bondline to zero strength
Resulting structural-ballistic interaction causes missile to explode off wing

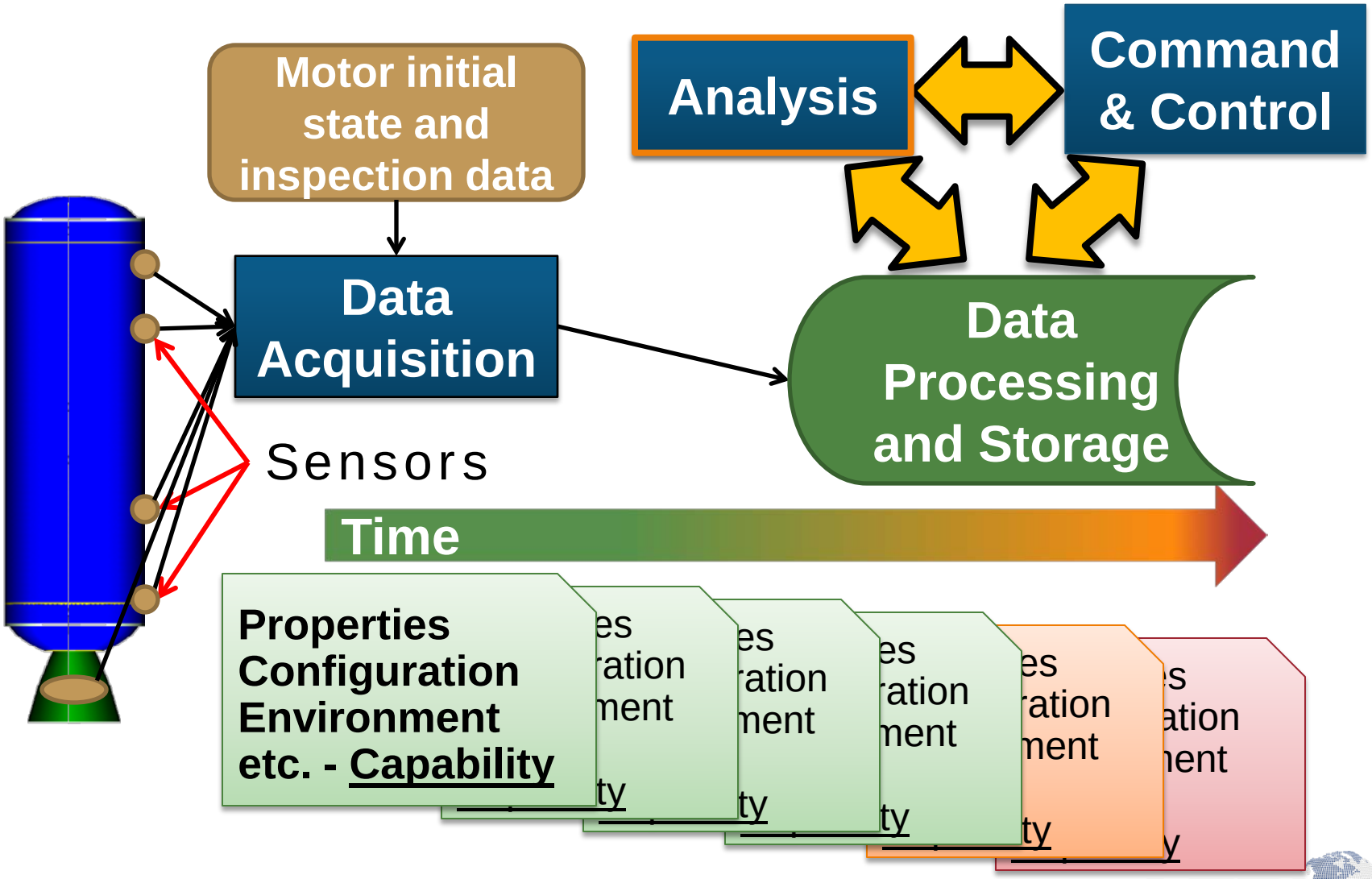
Cost: F-15 damaged, failure investigation

Background

- **In 1994, industry and government addressed the issue of service life prediction of rocket motors**
- **Consensus of the community was that the best predictions could be trusted to at most five years**
- **Only way to accurately improve predictions was to move to a mechanistic (first-principles) methodology**
- **Doubling the "look-ahead" window gives sufficient time to replace system without dramatically impacting readiness**

Accurate method of predicting motor life prevents unnecessary replacement of good motors based on conservative service life predictions

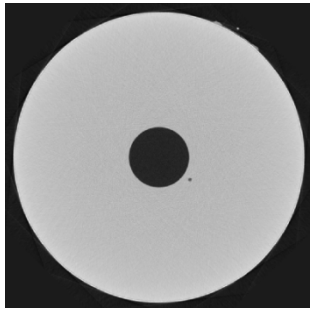
AFRL Missile System A&S



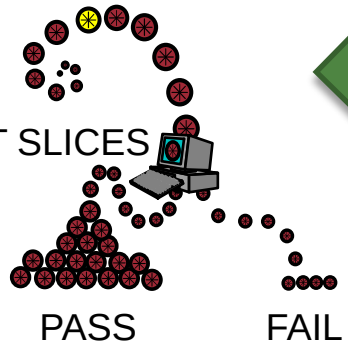
Analysis Programs Overview

NDE Data Processing Program (1997)

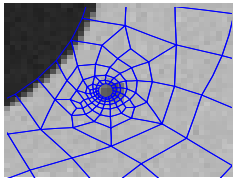
CT Flaw Detection



Automated Flaw Evaluation

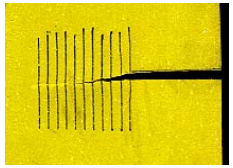


Critical Defect Assessment Program (1998)

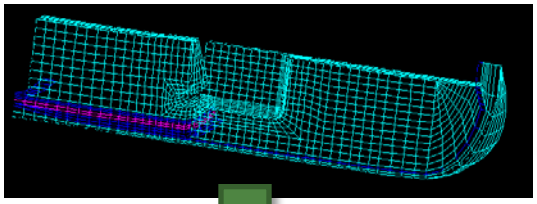


Automated 2D Flaw Meshing

Automated Fracture Propagation

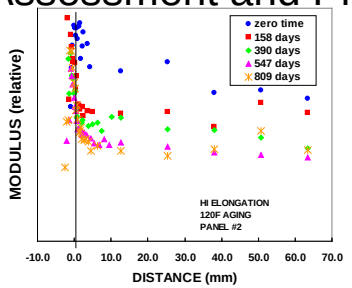


3D Structural/Ballistic Modeling



Service Life Prediction Technology Program (1997)

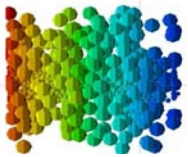
Chemical/Mechanical Property Assessment and Prediction



Polymer Mechanics

Nonlinear Viscoelastic Constitutive Modeling

Particle Packing



AMPT Task Order 4 (2006)

Dewetting, and multi-scale crack coalescence

SRM Service Life Estimate

Automated Multidisciplinary Solution Framework

Detects and evaluates flaws in real motors

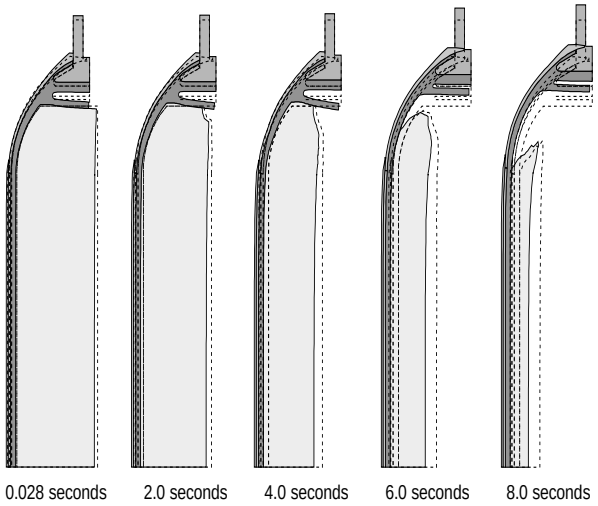
NDE Flaw Definitions

Predicts future chemical-mechanical state

Chemical Calculations

FEM Builder

FEM Builder controls software interaction



CFD

Thermal Analysis

Structural Analysis

Fracture Mechanics

Crack Combustion

Grain Burn Back

Multi-disciplinary
Multi-dimensional
Interaction

Predicts motor performance and environment

Predicts char, erosion, and thermal margins of safety

Predicts structural integrity and margins of safety

Analysis software developed transitioned to industry — used on operational and development programs

Sensor Development

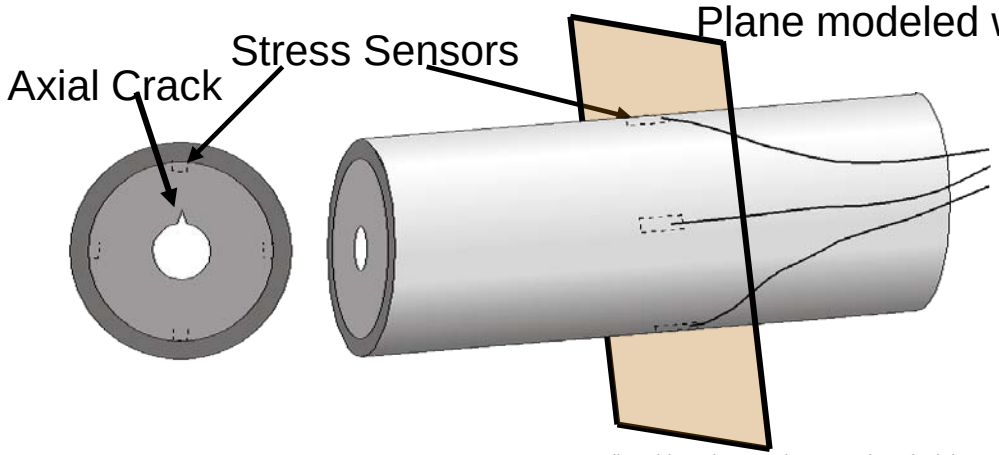
Instrumented, non-destructive life determination is the next step

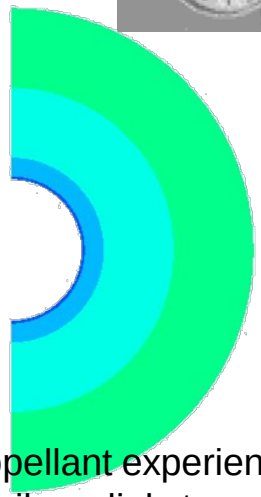
Questions that must be answered:

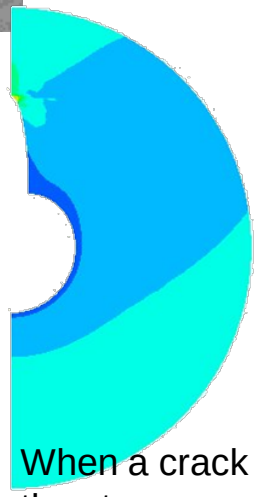
- **Effects of sensor on system safety and reliability**
- **Sensor optimization and placement**
- **Data acquisition, storage, transfer, and security**
- **Determination of minimal set of valuable data**

Sensor Number and Location Optimization

Analysis of sensor location, sensitivity requirements – Dr. Timothy Miller

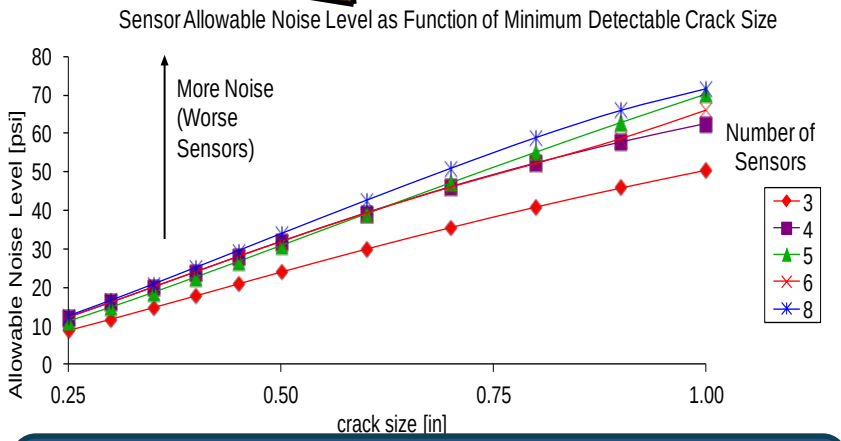






Propellant experiences tensile radial stresses as it tries to pull away from the case

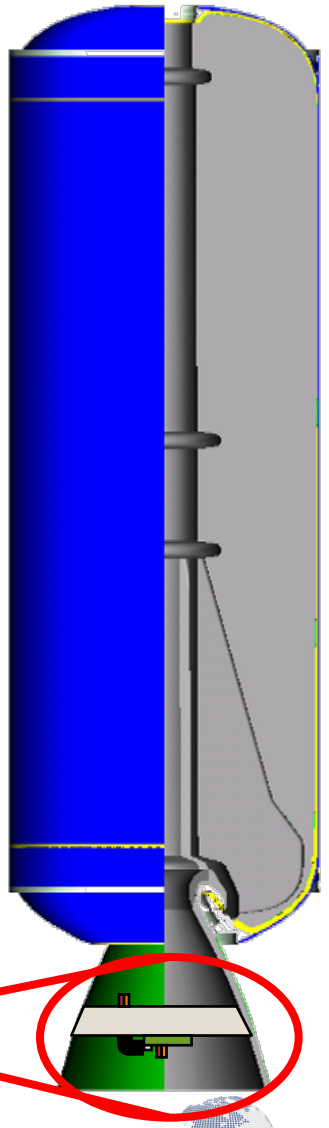
When a crack develops, the stresses are released near the crack.

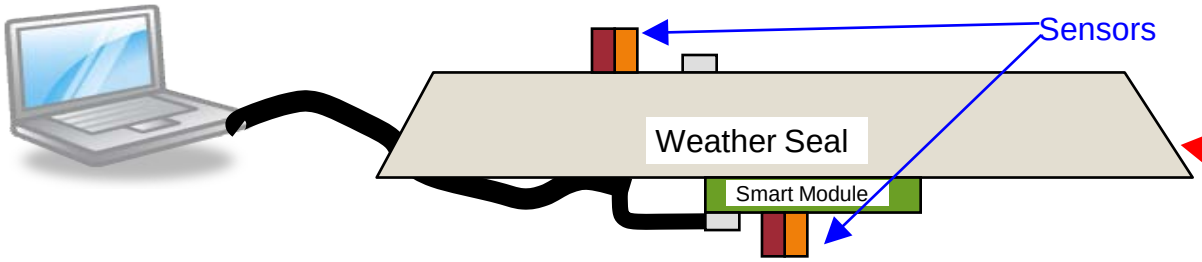


Relationship between crack size, number of sensors, sensor sensitivity

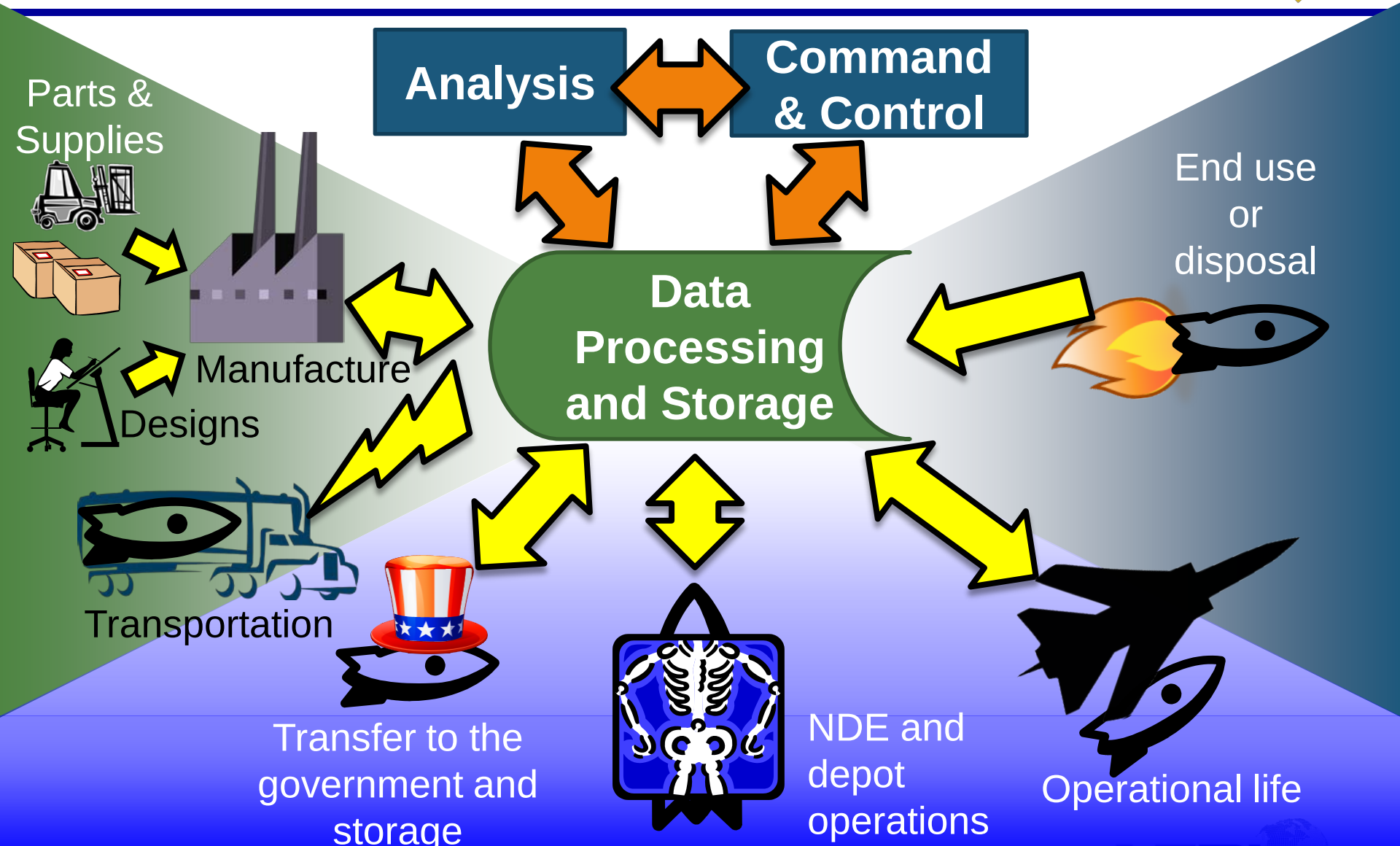
Smart Weather Seal

- **Small, light, and inexpensive with no batteries**
- **Electronics/sensors attached to weather seal**
- **Includes break-away connections for firing**
- **Initially includes temperature and humidity sensors, and accelerometer**





Lifecycle Data Management



Sensor Tech Needs

- **Modulus sensors:**
  - **Method to determine various mechanical moduli throughout the asset**
- **Chemical sensors:**
  - **A method to measure the chemical changes in the PLI are driven by chemical diffusion-reaction processes**
  - **Field measurements would be of substantial benefit**
- **Non-contact sensors**
  - **Compact, transportable systems to replace depot inspections with CT, UT, X-ray, or other techniques**
  - **External sensors to replace embedded sensors**

Analysis Tech Needs

- Flaw behavior during operation
  - Physics based models
  - Addition of new physics to modeling framework
- Enhanced coupling of modeling technologies
- Validation Data
  - Motor firing data
  - Physical property measurement

Summary and Conclusions

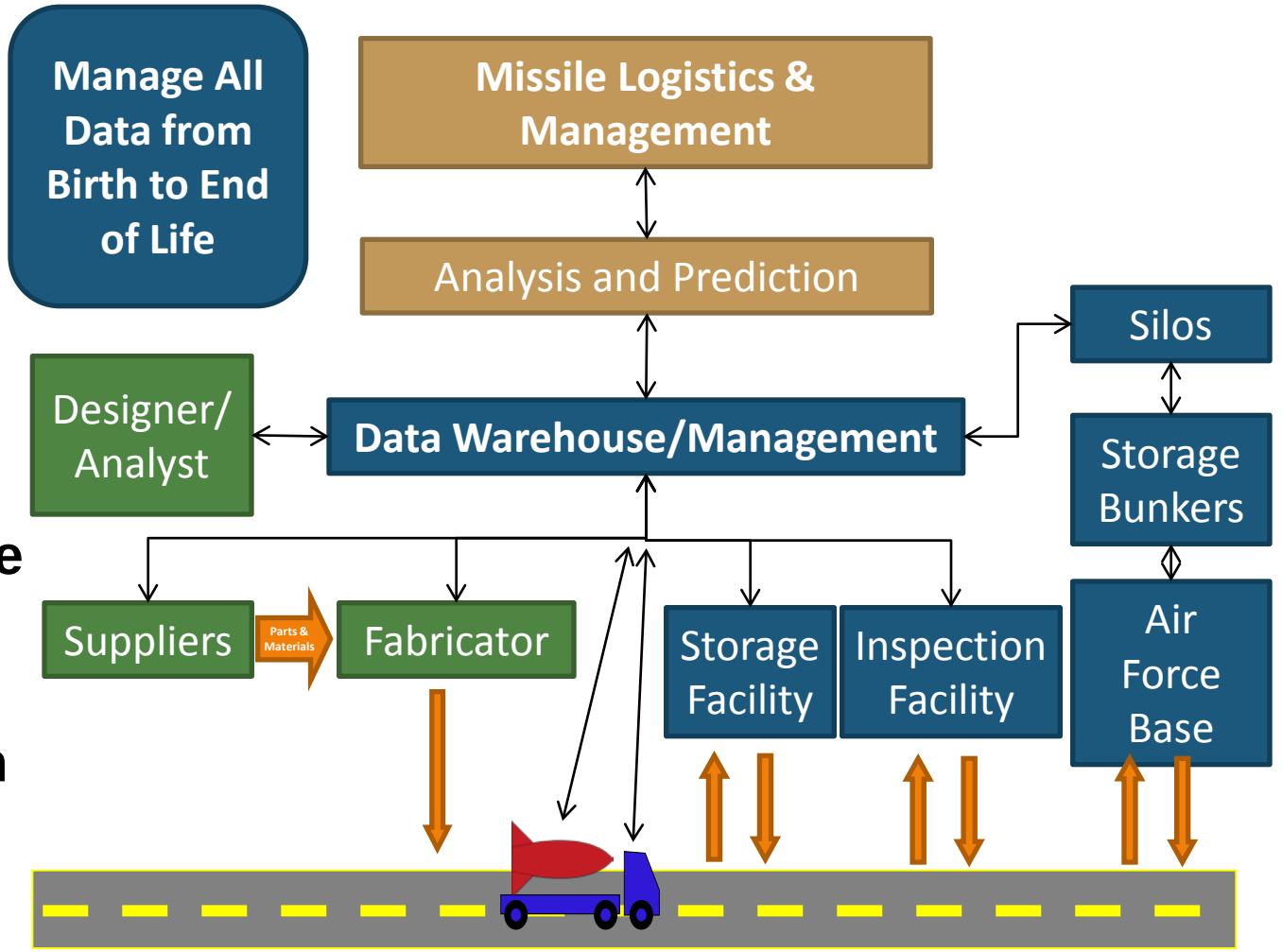
- Solid rocket motors are a unique and challenging environment for health monitoring
- Current AFRL aging and surveillance effort addresses analysis, sensors, and data management
- Future opportunities exist in the areas of:
  - Advanced analysis capabilities
  - Validation data
  - Sensors
  - Technology integration

Questions?

Other Possible Slides

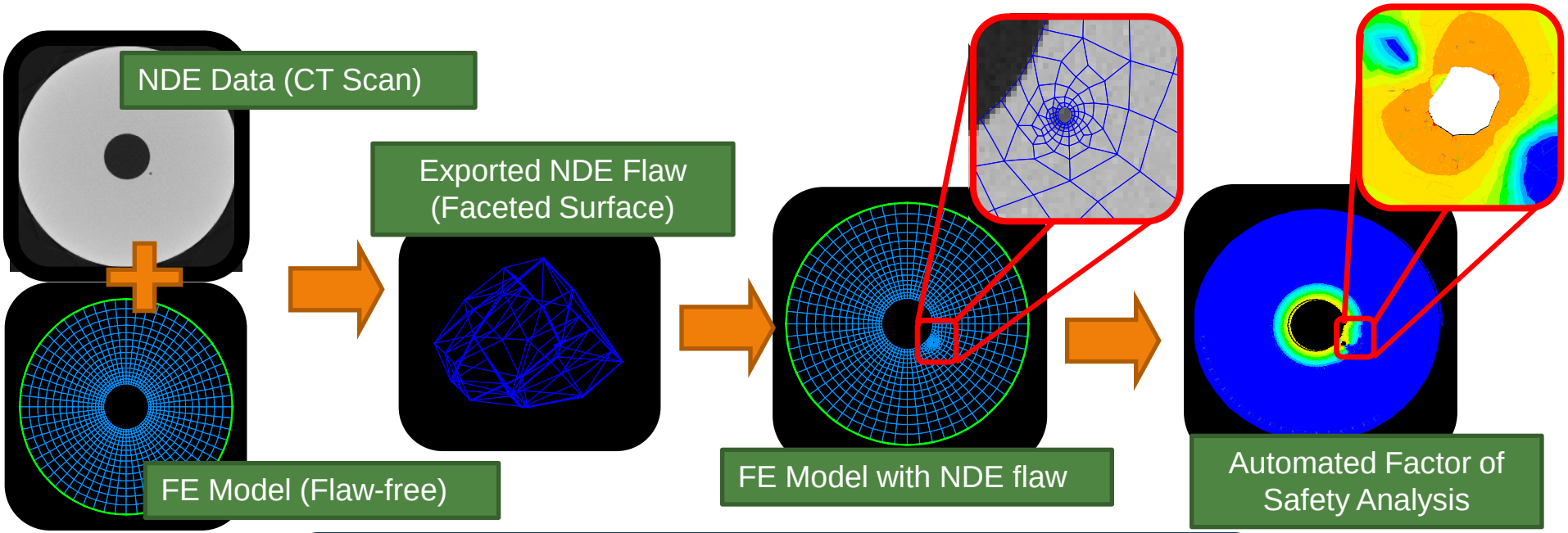
Data Manager System

- Security
- Policy control
- Modular software
- XML schema
- Journal-based feedback
- Tools to manage/retrieve
- Standards-based communication
- Structured, integrated data storage



Non-Destructive Flaw Assessment

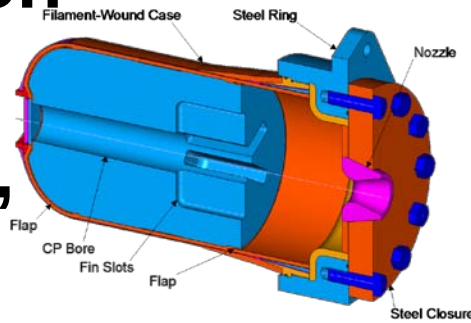
- **ANDES/2 code analyzes X-ray CT scan, detects voids, inclusions, and debonds**
- **Flaw data automatically incorporated into existing baseline model and analyzed**



ANDES/2 in daily use for motor inspections

Sensor Application/Modeling

- Demonstrate embedded sensors in near-production environment
- Bond strength test results
  - Multiple sensors embedded in SRM liner, tested in tension and shear
    - No failures through sensors
    - No change in bond system strength
    - No damage to sensors from storage/handling
- Demonstration of bore crack detection with bondline sensors
- 10” analog motors fired successfully, stored for long-term aging study



Aging and Surveillance Relationship to Other Work

1994 SOTA	A&S Programs Advancements
• Linear elastic constitutive model	• NLVE constitutive model • Mechanistic model for filled polymer constitutive behavior
• Uncoupled or manually coupled analyses • 0D or 1D Fluid Mechanics	• Coupled structures-ballistics-burnback analysis, fully 3D • Automated coupled solution, scriptable
• Automated Pass/Fail of CT scanned motors • Flaw resolution of 40 mils	• Automated analysis speed increased 50x • Flaw resolution increased
• Flaws, voids, fractures input and propagated by hand	• Flaws read from CT data • Fractures generated from continuum failure analyses • Automated 3D fracture propagation in mesh-free mode
• Material aging assumed to follow Layton (logarithmic) aging law • Maximum service life look ahead 5-years	• Future chemical state prediction from actual chemical processes • Material property changes from chemical/mechanical link • Service life look-ahead 10 years with 90% reliability/90% confidence

Integrated Motor Life Management (IMLM)

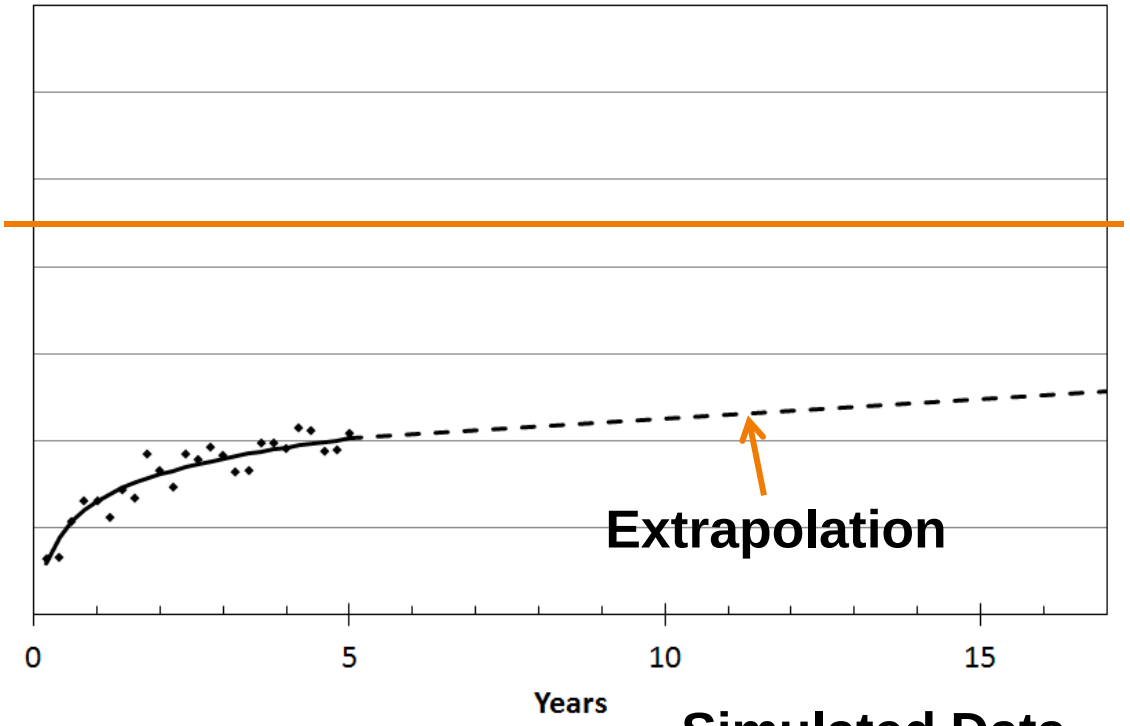
- Design a system to accurately predict the ability of a specific solid rocket motor (SRM) to perform its intended mission
- Task 1: Baseline the System
  - Identify high TRL sensors, analysis software, and other associated components necessary to deploy a prototype
- Task 2: Integration and Assembly of Prototype/Breadboard System
  - Assemble prototype/breadboard system using the proposed technologies

Integrated Motor Life Management (IMLM)

- **Task 3: Demonstrate Integrated Prototype on Motor Analogs**
  - **Demonstrate integrated prototype in relevant environments at a laboratory scale – confirm system capabilities**
- **Task 4: Demonstrate Integrated Prototype System in Relevant Environments**
  - **Subscale motors will demonstrate all aspects of the IMLM system**
  - **A representative scale motor will be analyzed and monitored while manufactured, aged, transported, transferred to the government, and tested**
  - **True prediction of performance will be conducted**

AFRL Strategic Missile A&S Approach Overview

- Empiricism cannot always predict future state
- Mechanistic method enables enhanced predictions
  - Mechanistic will not be worse than empirical approach



Simulated Data

AFRL Strategic Missile A&S Approach Overview

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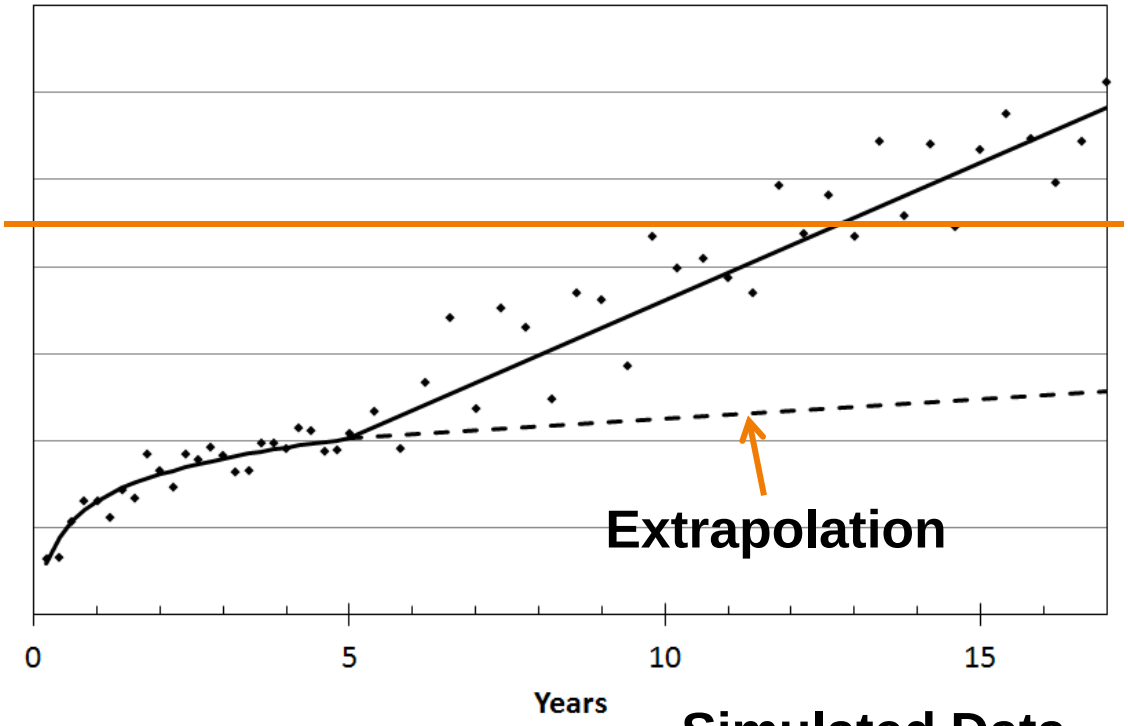

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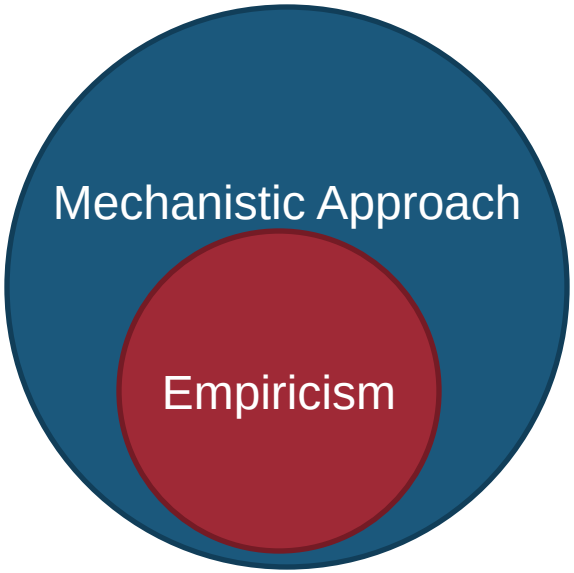

IMLM Program Schedule